The 2007 M5.4 Alum Rock, California, Earthquake: Implications for Future Earthquakes on the Central and Southern Calaveras Fault

David H. Oppenheimer
United States Geological Survey, MS – 977, 345 Middlefield Rd, Menlo Park, California, 94025 USA

William H. Bakun
United States Geological Survey, MS – 977, 345 Middlefield Rd, Menlo Park, California, 94025 USA

Thomas E. Parsons
United States Geological Survey, MS – 999, 345 Middlefield Rd, Menlo Park, California, 94025 USA

Robert W. Simpson
United States Geological Survey, MS – 977, 345 Middlefield Rd, Menlo Park, California, 94025 USA

John Boatwright
United States Geological Survey, MS – 977, 345 Middlefield Rd, Menlo Park, California, 94025 USA

Robert A. Uhrhammer
Berkeley Seismological Laboratory, 215 McCone Hall, University of California, Berkeley, California, 94720 USA

Abstract

The similarity of seismograms recorded by two seismic stations demonstrate that the 31 October 2007 moment magnitude **M**5.4 Alum Rock earthquake is a repeat of a 1955 M_L5.5 earthquake. Both occurred on Oppenheimer *et al.'s* (1990) Zone V "stuck patch" on the central Calaveras fault, providing critical support for their model of Calaveras fault earthquake activity. We suggest that Zone V fails only in a family of recurring **M**5.4-5.5 earthquakes. The 1955 and 2007 earthquakes are the penultimate and ultimate Zone V events. Earthquakes in 1891 and 1864 are possible earlier Zone V events. The next Zone V event is not expected in the next few decades; the mean forecast date is 2064 (2035-2104, 95% confidence range). We further suggest that Zones I, II, III, and IV fail in recurring **M**5.1-5.3, **M**5.6-5.8, **M**6.1-6.3, and **M**4.9-5.0 earthquakes, respectively. If our earthquake recurrence model is correct, the next Zone I event is overdue and could occur anytime, and **M**5-6 earthquakes should not occur on Zones II, III, and IV before 2014, 2012, and 2026, respectively. We cannot rule out the possibility that Zone VI, which lies at the southern end of the Mission Seismic Trend where the southern Hayward and central Calaveras apparently are connected at depth, fails aseismically or in large events on southern Hayward fault, such as last occurred in 1868, or in large events on the adjoining northern Calaveras fault segment.

Introduction

With the very notable exception of the 1989 moment magnitude **M**6.9 Loma Prieta earthquake and its associated pre-shocks and aftershocks, many of the earthquakes widely felt in the south San Francisco Bay region in the past 100 years have occurred on the Calaveras fault (Bakun, 2008). The felt earthquakes and the slip apparent along the Calaveras fault trace have attracted scientists and tourists alike. USGS fault trace maps (*e.g.*, Radbruch-Hall, 1974) guide visitors to offset curbs, fences, cracks in pavement, and damaged homes that extend in a straight line through the streets of Hollister. It is not uncommon for tourists and scientists to meet on the trace of the Calaveras fault. The first questions posed to the scientists are usually "Does this steady movement (fault creep) release the energy and prevent felt earthquakes?" and "When is the next big one?"

Oppenheimer *et al*. (1990) provided a model with which they attempted to answer these questions. They noted that the spatial pattern of microearthquakes occurring before the larger mainshocks on the Calaveras fault was similar to the pattern following the shocks and that the mainshock hypocenters were at 8-9 km depth near the base of the zone of microearthquakes (Figures 1 and 2). They also noted that the areas of co-seismic slip for the 1979 **M**5.7 Coyote Lake and 1984 **M**6.2 Morgan Hill earthquakes coincided with fault areas that were otherwise aseismic (Figure 2e). From these observations they proposed a model: persistent aseismic fault areas near the base of the seismogenic zone represent "stuck" patches on the fault surface that slip only during moderate earthquakes. The surrounding matrix of fault slipped frequently through creep and microearthquakes.

Oppenheimer *et al*. (1990) identified six stuck patches, numbered I to VI from south to north, where past and future **M**5-6 main shocks occur (Figure 1). They proposed a post-1910 rupture history for each: Zone I — an M_L 5.2 earthquake in 1949; Zone II — the **M**5.7 1979 Coyote Lake earthquake; Zone III — **M**6.2 earthquakes in 1911 and 1984; Zone IV — an M_L 4.9 event in 1943 and an **M**5.0 event in 1988; Zone V — a M_L 5.5 earthquake in 1955; Zone VI — no post-1910 **M**5-6 earthquakes that might have occurred on this Zone could be identified. They suggested that Zones I and VI were the most likely sites for the next **M**>5 Calaveras fault earthquakes and that the potential for Zone V was low.

On October 31, 2007 an **M**5.4 earthquake occurred on the Calaveras fault 8 kilometers northeast of Alum Rock. The 2007 Alum Rock earthquake is the largest earthquake in the San Francisco Bay region since the 1989 Loma Prieta earthquake and the first significant earthquake on the Calaveras fault since Oppenheimer *et al*. (1990) proposed their model of Calaveras fault earthquake activity. (A **M**5.0 Calaveras fault event on June 13, 1988 located 5 km to the south in Zone IV has also been called the "Alum Rock" earthquake; we will hereafter refer to this and other Zone IV events as "1988-type Alum Rock" earthquakes.) The purpose of this report is to document the support that the 2007 Alum Rock earthquake provides for Oppenheimer *et al*.'s (1990) model, extend the rupture history for Zones I-VI to pre-1910 earthquakes, and quantify forecasts for future felt earthquakes on the Calaveras fault.

The 2007 Alum Rock earthquake

Although little damage resulted, the October 31, 2007 (03:04:54 UTC) Alum Rock earthquake was recorded by more than 200 digital accelerographs deployed since the Loma Prieta event. Both the first-motion focal mechanism (Northern California Earthquake Data Center) and the regional moment tensor solution (Figure 3) for the 2007 Alum Rock earthquake (Hellweg *et al*., 2008, Northern California Earthquake Data Center) indicate predominant right-lateral strike-slip motion on a northwest-striking vertical fault consistent with rupture of the Calaveras fault. The quake nucleated slightly to the northwest of Zone V at a depth of 10.0 km when located using Hypoinverse (Klein, 2002) using identical velocity models as done by Oppenheimer *et al.* (1990) . When located with a double difference location method (2007, Hardebeck, personnel communication) the hypocenter depth is 8.6km (Figure 2c).

To gain insight into whether the earthquake ruptured into or away from Zone V, we use the method of Seekins and Boatwright (2008) to estimate directivity by analyzing peak ground acceleration (PGA) and velocity (PGV) data within 70 km of the earthquake recorded on strong-motion instrumentation operated by partners of the California Integrated Seismic Network (Figure 3). The PGA and PGV directivities are strong and clearly identify the NW-SE striking nodal plane (that is, the Calaveras fault) as the rupture plane. The PGA solution has a rupture velocity of 0.66β, where β is the shear velocity, with an up-dip component. The PGV solution has a rupture velocity of 0.82β

112 with a down-dip component. The PGA solution with the slower rupture velocity appears
113 more appropriate, largely because it is more closely aligned with the nodal plane.
114
115 The results of the directivity analysis and the Wells and Coppersmith's (1994)
116 relationship between **M** and subsurface rupture length indicate that the 2007 Alum Rock
117 rupture ruptured about 6 kilometers to the southeast of its hypocenter. The six-km-long
118 section of fault southeast of the hypocenter coincides with Oppenheimer *et al*.'s (1990)
119 Zone V.
120
121 Oppenheimer *et al*. (1990) concluded from S-P arrival time data at two seismic stations
122 that if the September 5, 1955 M_L5.5 earthquake occurred on the Calaveras fault, it
123 ruptured Zone V. If so, the 2007 **M**5.4 Alum Rock earthquake is a repeat of the 1955
124 earthquake. To confirm whether the 1955 and 2007 events both ruptured Zone V, we
125 scanned Wood-Anderson seismograms of the 1955 earthquake recorded at UC Berkeley
126 Seismological Laboratory seismic stations Mount Hamilton (MHC) and Berkeley (BRK).
127 After deconvolving the instrument response of the 2007 event recordings at MHC and
128 BRK and convolving in the Wood-Anderson response (Bakun *et al*., 1978), the synthetic
129 Wood-Anderson seismograms for the 2007 earthquake can be compared with the Wood-
130 Anderson seismograms for the 1955 earthquake. The first 180 seconds of the 1955
131 seismogram are too faint for meaningful comparison with the synthetic seismograms of
132 the 2007 earthquake (Figure 4). After 180 sec, the 1955 and 2007 seismograms at MHC
133 and BRK are nearly identical at frequencies greater than about 2 Hz. Assuming the "λ/4
134 Rule" of Geller and Mueller (1980), the centroids of these two events lie within a few

hundred meters of each other and confirm that the two magnitude 5.4-5.5 quakes ruptured Zone V.

Although the waveform comparison clearly demonstrates that the 1955 and 2007 earthquakes ruptured the same section of the Calaveras fault, it is instructive to see if the relocation of the 1955 earthquake is close to the 2007 hypocenter. We obtained the 1955 earthquake phase data from the Northern California Earthquake Data Center and used Hypoinverse (Klein, 2002) to relocate the earthquake with the same velocity model as used to locate the earthquakes shown in Figures 1 and 2. The sparse distribution of five stations that recorded the earthquake (Figure 5) made it necessary to reject any distance or residual weighting of the phase data in determining the solution in order to ensure a sufficient number of phase arrivals to locate the quake. Note that 3 of the 5 stations (FRE, PAC, and USF) ceased operation long before 2007, and therefore no travel-time corrections can be applied for these stations. The 1955 hypocenter has a focal depth of 8.7 km and locates 1.1 km from the 10-km-deep non-double-couple solution of the 2007 Alum Rock mainshock epicenter. The horizontal and vertical standard errors are 2.5 and 4.8 km, respectively, and encompass the computed separation of the 1955 and 2007 earthquakes. The small location error obtained for the 1955 earthquake is surprising, given that the number and distribution of seismic stations is far poorer than that of the 2007 earthquake. It also demonstrates that the timing of the 1955 phase data apparently is accurate to about +-0.2 seconds.

The 1949 earthquake – Zone I?

An M_L 5.2 earthquake occurred on 9 March, 1949 that Bolt and Miller (1975) located on the Calaveras fault. The quake was recorded by only 7 seismic stations in California and Nevada. No depth is reported by Bolt and Miller, as the location was determined with graphical methods in an era before the development of computers. To confirm whether the earthquake occurred on the Calaveras fault, we relocate it using Hypoinverse (Klein, 2002).

The 1949 earthquake phase data (Northern California Earthquake Data Center) contains multiple and conflicting P-arrival time readings for the same stations. Analysts at the Seismographic Stations of the University of California Berkeley apparently picked P and S arrivals on different seismographs operating at a single site (*e.g.*, Benioff and Wood Anderson seismographs at MHC) as well as on both horizontal channels of an instrument. To gain insight into the reliability of these conflicting observations, we first fixed the location of the 1949 earthquake at the location reported by Bolt and Miller (1975) and assigned a focal depth of 8.5km, typical of hypocentral depths of M>5 earthquakes on the Calaveras fault (Figure 2c-e). We then chose the P arrival time at each station that had the lowest traveltime residual. We suspect the variability in reported P arrival times is evidence of poor clock accuracy on individual channels. In particular, the P residuals observed at Mineral (MIN) range from 14-52 sec, exceeding the traveltime uncertainty expected for velocity model inaccuracy.

Having established a set of preferred P and S phase data, we relocate the 1949 earthquake with the same approach used above for the 1955 earthquake. We computed a focal depth of 12.7 km and 11.2 km with and without S readings, respectively. These off-fault epicenters are 6-8 km north-northeast of Bolt and Miller's (1975) location on the Calaveras fault, ("S_{49}" and "F_{49}" in Figure 5). Since depths of well-located earthquakes along the Calaveras fault in this region do not exceed 10 km, we fixed the depth to 8.5 km, but the epicenter still locates off the fault ("Z_{49}" in Figure 5). To gain additional insight into the epicentral uncertainty, we computed the RMS on a 1-km grid fixing the depth at 8.5 km and foregoing the use of any distance or residual weighting of phase data. Solutions within the 0.4sec RMS contour allow the location to be on the Calaveras fault (Figure 5), but it is not the minimum solution. Similar location results were obtained by varying the Vp/Vs ratio and eliminating S phase data.

Our analysis suggests that the clocks at all 5 stations were accurate to within a few tenths of seconds on 5 September 1955. In contrast, the inconsistent P-arrival times for the 1949 earthquake and its large location uncertainties suggest that the clock accuracy on 9 March 1949 may be too poor to obtain a reliable location using P arrival times. Given that there is essentially no seismicity since 1969 east of the Calaveras fault within the 0.4sec RMS contour shown in Figure 5, we suspect that clock errors are causing the 1949 earthquake to mislocate to the east of the fault. It is not possible to demonstrate that the1949 earthquake ruptured the aseismic patch of Zone I shown in Figures 1 and 2, but the data permit such an interpretation. We therefore assume that the 1949 earthquake did occur on the Calaveras fault near or a few kms north-northwest of the Bolt and Miller location.

Families of Recurring Earthquakes

Families of recurring earthquakes have been identified on faults in diverse tectonic regimes (*e.g.*, Okada *et al.*, 2003). One of the best studied families are the **M**6.0 Parkfield, California earthquakes that occurred on the San Andreas fault in 1881, 1901, 1922, 1934, 1966, and 2004 (Bakun *et al.*, 2005). Although details are limited for the earlier events, all of these events occurred on the same section of fault. Magnitudes for families of smaller recurring microearthquakes at Parkfield rarely vary by more than 0.1 from the family average (Nadeau and Johnson, 1998). Ellsworth (1995) summarized studies of repetitive failure of the same fault area in nearly identical earthquakes for moderate (magnitude 4-5) and microearthquakes (magnitude 1-2) in California and found that magnitudes range over about 0.5 M units.

In this study we assume that recurring earthquakes on the Calaveras fault share the characteristics of families of recurring earthquakes reported elsewhere in California. Bakun (2008) provides quantitative estimates of intensity center locations and magnitudes for pre-1911 earthquakes in the region using the method of Bakun and Wentworth (1997). There is very limited intensity data for almost all of these pre-1911 events, and the earthquake locations are highly uncertain, as shown by Bakun's (2008) confidence contours for location. We will show that the analysis of Oppenheimer *et al.* (1990) can be extended back in time for each of the five Zones. Because of the large

227 epicentral and magnitude uncertainty for many of the pre-1911 earthquakes, there are
228 multiple scenarios for extending Oppenheimer *et al.*'s (1990) model back through the
229 historical record, and there is no objective basis to select one preferred scenario (see
230 Table 1). Except for Zone II, in the following discussion we confine our potential
231 scenarios to those historical earthquakes where Bakun's (2008) 1-sigma uncertainty in
232 location and magnitude encompasses the **M** and location of Oppenheimer *et al.*'s (1990)
233 zones of repeating earthquakes.
234
235
236 ***Zone V (Alum Rock)***
237
238 The 1955 and 2007 events define the family of **M**5.4-5.5 Zone V earthquakes. Bakun
239 (2008) lists four possible pre-1955 Zone V earthquakes (Table 1); 26 February 1864, 5
240 March 1864, 21 May 1864, and 2 January 1891. For our purposes, the three 1864
241 earthquakes are indistinguishable as candidate **M**5.4-5.5 Alum Rock earthquakes. The
242 1955 and 2007 events occurred 52 years apart and it is reasonable that the 1891 event,
243 which occurred 64 years before the 1955 event, was the pen-penultimate Alum Rock
244 earthquake. The 1864 events occurred 91 years before 1955, or about twice the time
245 between the 1955 and 2007 events. It is reasonable then to assume that one of the 1864
246 events was the pen-pen-penultimate Zone V event.
247
248
249 ***Zone I (East of Gilroy)***

The March 9, 1949 M_L 5.2 earthquake is the only instrumentally located **M**> 5 earthquake that plausibly locates in Zone I. Bakun (2008) lists only one possible M 5.1-5.3 pre-1949 Zone I event: the 17 September 1888 earthquake. The earthquake catalog is, however, incomplete before 1905 for **M** < 5.5 earthquakes (Bakun, 1999), and several small earthquakes occurred in the period 1890-1910 near the southern and central Calaveras fault (Townley and Allen, 1939). Intensity data are not sufficient to locate these events, but M_I and a range of **M** can be estimated for assumed source locations. If on Zone I, the 1-sigma range in **M** for the earthquake on 15 January 1890 is 5.1-5.9. The earthquake on 11 December 1901 has a 1-sigma range in **M** of 5.2-5.8 for a location on Zone I. Thus, the 1888, 1890, and 1901 events are all viable penultimate Zone I earthquakes.

Zone II (Coyote Lake)

Surface slip and aftershocks for the **M** 5.7 1979 Coyote Lake earthquake were observed along the Calaveras fault from Coyote Lake to near San Felipe Lake where the Calaveras fault crosses California Highway 152 (Reasenberg and Ellsworth, 1982). McClellan and Hay (1990) reported triggered right-lateral slip on the Calaveras fault at Highway 152 near San Felipe Lake at the time of the 1989 Loma Prieta earthquake. Fresh northwest-striking cracks observed at Highway 152 after the 1984 Morgan Hill earthquake were interpreted as triggered slip (Galehouse and Brown, 1987; Harms *et al*., 1987). The Calaveras fault near Highway 152 apparently is a zone of frequent triggered slip, and it

would be surprising if the penultimate Zone II earthquake also did not trigger slip there. Bakun (2008) lists seven possible M 5.7 pre-1979 Zone II events: earthquakes on 26 February 1864, 5 March 1864, 21 May 1864, 24 May 1865, 26 March 1866, 2 January 1891, and 6 July 1899.

Fissures were reported on the Pacheco Pass road near San Felipe for the June 20, 1897 M_I6.3 earthquake (Toppozada *et al*., 1981). These fissures can be attributed to triggered slip, and the intensity data for the 1897 earthquake are consistent with a location on Zone II (Bakun, 2008). If the 1897 event occurred on Zone II, the 95% confidence range from Bakun's analysis is $5.7 \leq \mathbf{M} \leq 6.6$. That is, if the constraint on **M** is relaxed from 1 sigma to 2 sigma, the 1897 earthquake is also a viable penultimate Zone II event, as suggested by Oppenheimer *et al.* (1990).

Zone III (Morgan Hill)

The inter-event time, T, between the **M**6.2 1911 and 1984 Morgan Hill Zone III earthquakes is 73 years. The 1911 event is somewhat anomalous in that it occurred soon after the great 1906 San Francisco earthquake, punctuating a long period of seismic quiescence in the San Francisco Bay region that followed this **M**7.8 event (Harris and Simpson, 1998; Doser *et al*., 2008). Bakun (2008) lists five potential pre-1911 Zone III events: 26 November 1858, 24 May 1865, 20 June 1897, 11 June 1903, and 3 August 1903.

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298 ***Zone IV (1988-type Alum Rock)***

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300 The similarity of seismograms led Oppenheimer *et al.* (1990) to conclude that the 1943
301 M_L 4.9 and 1988 **M**5.0 earthquakes both occurred on Zone IV. Bakun (2008) lists only
302 one possible M 4.9-5.0 pre-1943 Zone IV event: the 5 March 1864 earthquake.

303

304 The earthquake catalog is incomplete before 1905 for **M**<5.5 earthquakes (Bakun, 1999),
305 but several small earthquakes occurred in the period 1890-1910 near the southern and
306 central Calaveras fault (Townley and Allen, 1939). Intensity data are not sufficient to
307 locate these events, but M_I and a range of **M** can be estimated for assumed source
308 locations. If on Zone IV, the 1-sigma range in **M** for an earthquake on 15 January 1890 is
309 4.6-5.4. If on Zone IV, the 1-sigma range in **M** for an earthquake on 11 December 1901
310 is 4.7-5.3. The 1890 and 1901 events are both viable pen-penultimate Zone IV
311 earthquakes.

312

313

314 ***Zone VI (south of Calaveras Reservoir)***

315

316 The instrumental record suggests no candidate **M**5 Zone VI earthquakes since 1910.
317 Bakun (2008) lists eight potential pre-1911 Zone VI events: 26 November 1858, 26
318 February 1864, 5 March 1864, 21 May 1864, 17 February 1870, 2 January 1891, 11 June

319 1903, and 3 August 1903. There is no particular reason to argue that any of them did
320 occur there. That is, there is no evidence that any independent **M**5-6 earthquake has
321 occurred on Zone VI since 1850.
322
323 Zone VI is located in the vicinity of the intersection of the Central Calaveras, Northern
324 Calaveras, and the southern part of the Hayward fault at depth. The trend of small
325 earthquake epicenters which connect the southern Hayward fault and the central
326 Calaveras fault at depth has been called the Mission Seismic Trend by Manaker *et al*.
327 (2005). Zone VI, as originally defined, could lie on the northern Calaveras fault, on the
328 southern Hayward at depth, or in a zone of complex deformation surrounding the
329 kinematically unstable joining of these three faults. The region to the north of the 2007
330 Alum Rock hypocenter and Zone V contains concentrations of distributed seismicity not
331 easily attributed to individual structures (Figure 1), suggesting that the intersections of
332 these three faults may be a complex zone of distributed deformation spanning a distance
333 of 7-10 km along strike.
334
335 Zone VI may also be different from the Zones I–V to the south in that it may only
336 undergo aseismic deformation. It is also possible that Zone VI fails seismically, but that
337 the loading rate is low and the repeat time is greater than about 100 years. Perhaps Zone
338 VI fails in conjunction with large earthquakes on the northern Calaveras or Hayward
339 faults. If Zone VI slips in association with large Hayward fault earthquakes such as the
340 1868 event, then the Zone VI "family of recurring earthquakes" would include events at
341 the times of the eleven surface rupturing **M**6-7 events on the Hayward Fault reported

342 from paleoseismic studies in Fremont (Lienkaemper and Williams, 2007). Alternatively,
343 Zone VI might fail in conjunction with surface rupturing events on the Northern
344 Calaveras fault, such as those recorded at Leyden Creek (Kelson *et al.* 1993, 1996;
345 Simpson *et al.*, 1999; William Lettis & Associates, Inc., 2005). If the ruptures of large
346 events on either fault stop just north of Zone VI, Zone VI might be a good candidate
347 location for a significant aftershock.
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349

350 Earthquake Forecast for Calaveras Fault Zones (I-V)

351
352 Observation of families of recurring earthquakes on Calaveras fault segments implies that
353 future events can be forecast. Further, if earthquakes occurrence is quasi-periodic, then
354 earthquake probability is time-dependent. Time dependence emerges from the concept of
355 elastic rebound, where time is required to recharge stresses released in the last large
356 earthquake. Under a time dependent process, the probability of an earthquake occurring is
357 lowest just after the last large earthquake, and then increases over the duration of the
358 mean recurrence interval. This theoretical concept has been accepted as a component of
359 earthquake forecasting in California (*e.g.*, Working Group on California Earthquake
360 Probabilities (WGCEP), 2003; 2008), and appears consistent with the paleoseismic
361 record on the adjacent Hayward fault (Parsons, 2008a).
362
363 A time-dependent earthquake probability calculation sums a probability density function
364 that distributes around some mean interevent time (μ), with the width of the distributions

representing inherent variability (α) on recurrence. Optimally, we would have enough recorded earthquake intervals to unequivocally define the shape of recurrence distributions on faults. However, doing that requires at least ~25-50 intervals to gain the necessary resolution (*e.g.*, Matthews *et al.,* 2002). For zones along the Calaveras fault, we can only associate earthquakes with particular zones with any confidence during the period between 1911 and present, which restricts the number of intervals for most zones to no more than 3. If we are willing to specify general functional forms of recurrence distributions in advance, then it is possible to overcome the limited sampling problem using Monte Carlo techniques (Parsons, 2008b). Here we use Brownian Passage Time (inverse Gaussian) distributions (Kagan and Knopoff, 1987; Matthews *et al.*, 2002) to represent time dependence (after WGCEP, 2003, 2008) as,

$$f(t,\mu,\alpha) = \sqrt{\frac{\mu}{2\pi\alpha^2 t^3}} \exp\left(-\frac{(t-\mu)^2}{2\mu\alpha^2 t} \right), \qquad (1)$$

where μ is recurrence interval, α is coefficient of variation, and t is time. The Brownian Passage Time distribution is nearly indistinguishable from the also commonly applied lognormal distribution for earthquake recurrence.

To find the most likely recurrence parameters, a series of distributions that covers all reasonable mean recurrence intervals is developed (1 yr to 500 yrs). Time dependent distributions are characterized by two parameters (Equation 1), and are thus also constructed across coefficient of variation values between 0.01 and 0.99 for each mean recurrence interval. Groups of earthquake dates are randomly drawn millions of times

388 from each possible recurrence distribution and assembled into sequences. With this
389 method, sequence means are identified directly from the parameters of parent
390 distributions rather than from taking arithmetic means of sequences. This process
391 overcomes the sampling bias problem of skewed distributions and is more effective than
392 bootstrapping over the dating uncertainty intervals, which repeats and stacks means from
393 insufficient samples (Parsons, 2008b).
394
395 Every recurrence distribution is randomly sampled 5 million times for intervals between
396 Calaveras fault earthquakes for Zones I to V. Those sequences that have one earthquake
397 occurring in order during each observed event year, and no earthquakes in the intervals
398 between events are tallied, and a ranking of matches vs. mean recurrence and coefficient
399 of variation to the observed record is produced (Figure 6). Further, sequences are only
400 tallied if no simulated event times occur in the open intervals between the first post-1911
401 event and the latest possible historic earthquake that could have happened on each
402 segment from the analysis of Bakun (2008). Similarly, sequences are only tallied if no
403 simulated event times happened in the open intervals between the last observed
404 earthquake year for each zone and the present.
405
406 Monte Carlo analysis of Zones I-V along the Calaveras fault reveals broad arrays of
407 allowable recurrence times for each zone (Figure 6). Mean recurrence times are quite
408 similar across the zones and range from 57 to 73 years (Table 2). We find high
409 coefficients of variation, 0.8-0.9, for all zones, which suggests that if the renewal model
410 we apply is correct, then recurrence along Calaveras fault is relatively aperiodic.

411

412 We calculated 10-yr and 30-yr probability values for Calaveras fault Zones I-V using the
413 distribution parameters from Table 2 and integrating Equation 1, which generated
414 distributions of possible answers (Figure 6c). The distributions allow us to determine the
415 sensitivity of probability calculations to uncertainty in recurrence interval parameters. We
416 report the mean values and confidence bounds taken from distributions in Table 3. We
417 also forecast most likely intervals within which Calaveras fault earthquakes are expected
418 to occur, based on the times of the last earthquakes by zone and our analysis of
419 recurrence intervals. We have thus made testable assumptions about the time dependent
420 process (Brownian Passage Time) and the existence of characteristic, recurring
421 earthquakes on 5 Calaveras fault segments. Our calculations suggest that an event is
422 expected in Zone I at any time (Table 3). Further, if our model is correct, then we should
423 not expect to see M~5 earthquakes occurring in Zone II before 2014, Zone III before
424 2012, Zone IV before 2026, nor Zone V before 2035. Conversely, if a M~5 quake should
425 strike in Zones II-V prior to those expected dates, then our model is invalid at 95%
426 confidence.

427

428 Discussion

429

430 *Possible Effects of the 1868, 1906, and 1989 Earthquakes on the Calaveras Fault*

431

432 In identifying potential families of repeating earthquakes, we have not considered the
433 possible effect that large earthquakes in the region might have had in advancing or

retarding occurrence times of Calaveras events. For example, the 1906 **M**7.8 earthquake had a profound effect on seismicity in the San Francisco Bay region (Bakun, 1999). In the 70 years before 1906 there were seventeen M≥6 events in the region, but in the following 101 years there have been only five. This post-1906 seismic quiescence has been attributed to a stress shadow cast on Bay Region faults which were relaxed by the coseismic stress changes from the 1906 (*e.g.*, Jaume and Sykes, 1996). Modeling suggests that visco-elastic relaxation in the lower crust and mantle can, depending on geometry, further relax neighboring faults over a period of years and decades (Kenner *et al.*, 2000; Parsons, 2002; Pollitz *et al.*, 2004), but the low rate of earthquakes in the region since 1989 is consistent with a lingering 1906 stress shadow.

Ellsworth (1995) notes that the interval between repeats of recurring small earthquakes is not random and is likely related to the loading rate. In particular, nearby larger earthquakes affect the loading rate and the timing of subsequent nearby repeating small earthquakes. We note that the time between the 1891 and 1955 Alum Rock events on Zone V, 64 years, is longer than the time between 1858 (or 1864) and 1891 events, and longer than the 52 years between the 1955 and 2007 events. The intervals are consistent with the 1906 earthquake delaying the 1955 Alum Rock earthquake by about a decade. If this suggested timing delay on Zone V due to 1906 is appropriate for Zone II, then the 1979 Coyote Lake earthquake would have occurred later than expected. That is, the 82 years between 1897 and 1979 may be longer than the average time between Zone II events.

457 It is not clear how the time between the 1911 and 1984 Zone III events might have been
458 affected by the 1906 earthquake because both events occurred after 1906. The 1911
459 event, one of the five M≥6 events in the Bay region since 1906, does pose a puzzle,
460 falling only 5 years after 1906 on a segment of the Calaveras fault that coseismically was
461 significantly relaxed (Simpson, 2003; Pollitz *et al.*, 2004). Several explanations that have
462 been offered for this paradox are summarized by Doser *et al.* (2008), including dynamic
463 triggering and rate-and-state non-linear failure behavior. Although there is good
464 agreement on the estimated size of the coseismic relaxation at the site of the 1911
465 earthquake, there is considerable question as to the rate of the loading that is re-stressing
466 the fault to pre-1906 levels. Elastic models that don't take account of the large amount of
467 aseismic slip on the Calaveras fault yield recovery times ranging from several years to
468 several decades, depending on model assumptions and location along the fault (Simpson,
469 2003). Viscoelastic models that don't account for aseismic slip tend to yield recovery
470 times ranging from decades to a century (Parsons, 2001; Pollitz *et al.,* 2004). Hori and
471 Kaneda (2001) offer a simple model that incorporates aseismic slip on the Calaveras fault
472 and use it to amplify the tectonic loading rate on the stuck patches, so that stress could
473 recover to pre-1906 levels within several years —in time for the 1911 hypocenter to be
474 out of the stress shadow. However, Doser *et al.* (2008) suggest that creep rates at
475 Hollister after 1906 were retarded until 1923, which fails to explain the timing of 1911
476 either (although Hollister is about 50 km southeast of Zone III where the 1911 event
477 occurred).
478

The moment of the 1989 **M**6.9 Loma Prieta earthquake was ~30 times smaller than that of the 1906 event and presumably would have had a smaller effect on the Calaveras fault. There were , however, notable changes in regional seismicity and creep rates on the Calaveras fault after the 1989 earthquake (Reasenberg, 1997), but most did not persist for more than a few years. Quantitative estimates of the recovery time on the Calaveras fault after 1989 using simple elastic models range from 2-4 years (Simpson, 2003).

The 1868 **M**6.8-7.0 Hayward fault earthquake could also have had an effect on subsequent Calaveras fault seismicity, especially on Zone VI. If the 1868 rupture on the southern Hayward fault extended southward along the Mission Seismic trend, it might have included Zone VI or perhaps triggered aftershocks on Zone VI. Zones V and IV might also have been affected.

Evidence for large earthquakes on the Calaveras fault

The scenarios for earthquakes on the Calaveras fault considered in this paper have, with the possible exception of Zone VI, been based on the hypothesis of repeating moderate M5-6 earthquakes on spatially-static stuck patches. Trenching studies at San Ysidro Creek in Zone I raise the possibility of three surface rupturing earthquakes between 2,000 to 4,000 years ago with right-lateral offsets of 2-2.5 m (Kelson *et al.*,1998, 1999; Kelson, 2001). These offsets were inferred from locations of four late Holocene paleochannels. If due solely to a single event, offsets of this size would be consistent with M~7

502 earthquakes (Wells and Coppersmith, 1994). Given the location of these observations in
503 Zone I near the south end of the fault, it may be possible to reconcile the idea of frequent
504 (T ~50-100 years) moderate earthquakes on the Calaveras with occasional (T ~2000 –
505 3000 years) large earthquake if the large events nucleate elsewhere and rupture into the
506 southern Calaveras fault.
507
508
509 ***Earthquake migrations***
510
511 The proposed scenarios for Zones I-V displayed in Figure 7 suggest a south-to-north
512 progression of earthquake nucleation for the 1897-1955 period, and then for the 1979-
513 2007 period. Du and Aydin (1993) estimated static stress changes accompanying the
514 1979, 1984, and 1955 events, and showed that, although the changes caused by one event
515 at the site of the next were not large enough to explain the observed stress drops, the
516 changes were consistent with triggering in the northward progression of these
517 earthquakes. The location-progression pattern is similar to earthquake migrations
518 observed on the Northern Anatolian fault from 1939-1992 (Toksöz *et al.* 1979; Stein *et*
519 *al.* 1997) that have been attributed to stress triggering. We also note that the 1979, 1984,
520 and 2007 Calaveras fault earthquakes all ruptured toward the southeast, similar to a
521 directivity bias observed for microearthquakes on a nearby reach of the San Andreas fault
522 (Rubin and Gillard, 2000). Rubin and Gillard (2000) suggested that this bias could be
523 caused by a contrast in material properties across the fault, a possibility that has been
524 questioned by other workers (Harris and Day, 2005). Some studies have suggested that

such directivity could result from fault geometry, fault offsets, and interaction of the rupture surface with nearby faults and fault strands (*e.g.*, Bakun *et al.*, 1980; Reasenberg and Ellsworth, 1982; King and Nabelek, 1985). A better understanding of this phenomenon might help us better assess the earthquake hazard on the Calaveras fault.

Consistency test of the Zonal MRI calculations with the historic catalog

Bakun (2008) identified locations of pre-1911 earthquakes on Calaveras fault zones using analysis of intensity/damage observations. The time-dependent, characteristic rules of our forecast model require each Calaveras fault segment to host periodic, similar-magnitude earthquakes. We can therefore examine the historical occurrence of Calaveras fault earthquakes in terms of the magnitudes and most likely locations as determined by Bakun (2008) to ensure that the mean recurrence estimates we make with Monte Carlo analysis can be reconciled with the historical catalog.

Following our model rules, magnitude and location uncertainty allow the possibility that historic earthquakes may have occurred on multiple Calaveras fault zones (Table 4). We examined 784 potential combinations of earthquakes across 5 Calaveras fault zones and by eliminating all scenarios that put the same earthquake on two different zones, we emerged with 134 event sequences that were fully compatible with our recurrence model. The exceptions are two 1903 earthquakes (11 June and 3 August), which by their magnitudes, were assumed only to have occurred on Zone III. These events, in

548 combination with the instrumentally-located 1911 shock on the same segment, are all
549 closer in time than the 95% confidence range on mean recurrence interval (28-105 years).
550 Therefore either the time-dependent, characteristic recurrence model we apply is invalid
551 for Zone III, or the 1903 earthquakes occurred on another fault than the Calaveras.
552

Conclusions

The October 31, 2007 **M**5.4 Alum Rock earthquake provides critical support for Oppenheimer et al.'s (1990) model of earthquake activity on central and southern segments of the Calaveras fault. The epicenter is located on the Calaveras fault near the northwest end of Oppenheimer *et al*.'s (1990) Zone V. Peak ground acceleration and peak ground velocity data indicate strong directivity along the Calaveras fault toward the southeast. The typical subsurface rupture length for **M**5.4 strike-slip fault ruptures is about 6 kilometers. That is, the 2007 Alum Rock rupture extended about 6 kilometers southeast of the epicenter along the Calaveras fault, coincident with Oppenheimer *et al*.'s (1990) Zone V.

Oppenheimer *et al.* (1990) had concluded that if the September 5, 1955 M_L5.5 earthquake occurred on the Calaveras fault, it had ruptured Zone V. If so, the 2007 **M**5.4 Alum Rock earthquake is a repeat of the 1955 earthquake. Waveforms of the 2007 **M**5.4 Alum Rock earthquake do, in fact, replicate the waveforms of the M_L5.5 1955 earthquake. We suggest that Zone V fails in recurring **M**5.4-5.5 earthquakes. The 2007 and 1955 earthquakes are the ultimate and penultimate events in a family of recurring Zone V earthquakes. No other **M**5 events occurred on Zone V in the post-1910 instrumental record. Analyses of macroseismic data suggest several possible earlier **M**5.4-5.5 Zone V events. The January 2, 1891 earthquake is a candidate pen-penultimate Zone V event and there are three events in 1864 that might be a pen-pen-penultimate Zone V event. Using a time-dependent earthquake probability calculation for the instrumental (post 1910)

574 record, we estimate that the next **M**5.4-5.5 Zone V event is not likely to occur any time
575 soon. The mean forecast date is 2064 and the 95% confidence range is 2035-2104.
576
577 We suggest further that Zones I-VI all fail in their families of recurring earthquakes:
578 Zone II in recurring **M**5.6-5.8 events, Zone III in recurring **M**6.1-6.3 events, and Zone IV
579 in recurring **M**4.9-5.0 events. (Zones I and VI are not easily characterized, and are
580 summarized below.) **M**5 and larger earthquakes on the central and southern Calaveras
581 fault segments occur only in these zones; other fault segments fail only in small events
582 and in aseismic slip. If infrequent **M**7 events rupture the central and southern Calaveras
583 fault segments, those hypothetical events originate elsewhere and rupture into the central
584 and southern Calaveras fault segments.
585
586 The mean forecast date (95% time interval range) for Zones II, III, and IV is 2052 (2014-
587 2092), 2046 (2012-2089), and 2058 (2026-2097), respectively. If **M**5 events occur in
588 zones II-V before the start of the 95% interval, then our model (families of recurring
589 earthquakes on each zone and a Brownian Passage Time stress renewal process) is
590 invalid at the 95% confidence level. If our model is correct, we should not expect **M**5
591 events on Zone II before 2014, on Zone III before 2012, on Zone IV before 2026, or on
592 Zone V before 2035.
593
594 The March 9, 1949 M_L 5.2 event is the only instrumentally located Zone I event, but we
595 cannot demonstrate that it occurred on the Calaveras fault rather than off the fault a few
596 kilometers to the northwest. Although possible pre-1911 Zone I events have been

identified, No **M**5 Zone I events occurred in the 1911-1949 period. If on the Calaveras fault, our forecast calculation suggests that the next **M**5.1-5.3 Zone I event is overdue and could occur at any time.

Zone VI poses special problems. No **M**5-6 event has occurred on Zone VI since 1910. Although any of several possible 1850-1911 events might have occurred on Zone VI, there is no reason to conclude that any did occur there. Zone VI lies within a trend of small earthquake epicenters, sometimes called the Mission Seismic Trend, where the southern Hayward fault and the central Calaveras fault apparently are connected at depth. We cannot rule out the possibility that Zone VI is fundamentally different. Perhaps it only fails aseismically, or only in association with infrequent large northern Calaveras fault segment events. Perhaps Zone VI only fails in association with large events on the southern Hayward fault, such as last occurred in 1968.

Acknowledgments

We are grateful to the staff of the Northern California Earthquake Data Center for providing access to the historic earthquake catalog and, likewise, Felix Waldhauser and David Schaff for providing access to their double-difference catalog. We thank Fred Pollitz for calculating the stress shadow on the Calaveras fault caused by the 1906 earthquake, and Jeanne Hardebeck for providing the double difference location of the 2007 Alum Rock earthquake. Thanks to Nick Beeler and Bill Ellsworth for constructive reviews and to Roland Burgmann, Russ Graymer, and Keith Kelson for numerous helpful comments.

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Figure Captions

Figure 1. Seismicity in the south San Francisco Bay region, California, recorded by the USGS Northern California Seismic Network (NCSN) between 1984 and 2003 relocated using the double-difference technique (Waldhauser and Schaff, 2008). Oppenheimer *et al.*'s (1990, Figure 1) Zones I-VI along the Calaveras fault are shown. Epicenters of moderate earthquakes in Zones I – VI since 1910 are indicated by stars and dates.

Figure 2. Map views and cross-section views of the Calaveras fault looking from southwest toward the northeast. a) Map view showing double difference relocated seismicity from 1984-2003 (Figure 1); events within 2 km of a generalized, simple 3D Calaveras fault surface are highlighted in black (surface is not shown in the figure). b) Map view showing double difference seismicity below 5 km depth, with epicenters of most recent moderate earthquake in Zones I-V shown as stars. c) Cross-section view of double difference earthquakes within 2 km of a generalized Calaveras fault surface. d) Composite of the three panels from Figure 4a,c,e in Oppenheimer *et al.* (1990), showing NCSN seismicity for various time periods. e) Composite of the three panels from Figure 4b,d,f in Oppenheimer *et al.* (1990).

Figure 3. Symbols indicating the amplitude of the residual PGA and PGV values are plotted at the azimuths and vertical takeoff angles of the S-waves. Circles indicate amplified ground motions; crosses indicate de-amplified ground motions. Because we restrict the station distance to within 70 km of the hypocenter, most takeoff angles are vertically upward. However, the takeoff angles to the more distant stations can be slightly downward. The lines with arrow heads represent upward rupture direction. The longer the line, the more horizontal the rupture direction. The 2σ uncertainty areas enclose the arrow head and extend into the lower hemisphere for PGV. The rupture velocity "v" is shown in terms of the shear velocity β. The thick, perpendicular lines show the nearly vertical nodal planes of the pure strike-slip moment tensor solution (Hellweg *et al.*, 2008). The strike, dip, and rake are shown adjacent to each nodal plane.

Figure 4. Comparison of the waveforms from the 2007 and 1955 Alum Rock events. Scanned images of helicorder recordings are in grey: a) the 1955 UC Berkeley Wood Anderson seismographs for the EW channel at station BRK (Berkeley) at an epicentral distance of 65 km and b) NS channel at MHC (Mount Hamilton) at an epicentral distance of 15 km. The red seismograms are synthetic Wood Anderson records from the 2007 earthquake derived from the broadband channel for BRK and acceleration channel for MHC because its broadband sensor clipped. The 1955 record is too faint for comparison until the first enlarged frame on each seismogram. After that time the two waveforms are essentially identical. The orthogonal channels for BRK and MHC recordings of the 1955 and 2007 quakes are also similar but are not shown.

Figure 5. Map of stations (solid diamonds) that recorded the 1949/03/09 M_L 5.2 and 1955/09/05 M_L 5.5 earthquakes, and epicenters (squares) of the 1949, 1955, and 2007/10/31 M_w 5.4 earthquakes (respectively "49", "55", and 07"). Bolt and Miller's

(1975) locations are denoted with solid squares labeled B&M. RL_{55} and HI_{55} denote, respectively, relocation and non-double difference Hypoinverse (Klein, 2002) locations of the 1955 and 2007 earthquakes. Inset: Epicenters (small dots) from 1969-2009 and RMS contours for solutions of the 1949 earthquake fixed on a 1 km grid at a depth of 8.5 km with S data. Z49, S49, and F49 denote the relocations of the 1949 earthquake with, respectively, a fixed depth of 8.5 km, no depth constraint and no S readings, and no depth constraint.

Figure 6. (a) Distribution of possible recurrence intervals for Calaveras fault Zone III assuming a Brownian Passage Time stress renewal process. By counting through the distribution we can determine confidence intervals on recurrence. In (b) the distribution of coefficients of variation (COV) are given. For all Calaveras zones we find high COV values, implying that the renewal process on the Calaveras fault is relatively aperiodic. In (c) the distributions of 10-yr and 30-yr probabilities are shown. From these distributions, mean values and uncertainty estimates related to recurrence interval and COV parameter ranges can be expressed (Table 2).

Figure 7. Calaveras fault earthquakes since 1850. Historical events are shown as open stars, instrumentally-recorded events as black filled stars, and forecast events as open circles with vertical lines indicating the 95% confidence interval in time (Table 3). Gray areas indicate the extent of Oppenheimer *et al.*'s (1990) zones I-VI. Black arrows pointing to the right adjacent to some events indicate the directivity of the rupture where known. Diagonal arrows with dashed lines indicate an apparent progression of events from south to north. Events before about 1960 have uncertainties in location of 10 km or more, except for the 1943 and 1955 events where waveform comparisons with recent events allow for more precise locations.

Table 1. Calaveras Fault earthquake recurrence scenarios‡

Zone	Date	M	M 1σ (2σ) range
I†	17 September 1888	5.2	4.9-5.5
	15 January 1890†	5.5	5.1-5.9
	11 December 1901†	5.5	5.2-5.8
	9 March 1949	M_L5.2	5.1-5.3
II	26 February 1864	5.6	5.0-6.1
	5 March 1864	5.5	5.3-5.7
	21 May 1864	5.9	5.6-6.2
	24 May 1865	5.9	5.6-6.2
	26 March 1866	5.5	5.3-5.7
	2 January 1891	5.8	5.5-6.0
	20 June 1897	M_I6.3	6.0-6.4 (5.7-6.6)
	6 July 1899	5.8	5.6-6.0
	6 August 1979	5.7	5.6-5.8
III	26 November 1858	6.3	6.1-6.5
	24 May 1865	5.9	5.6-6.2
	20 June 1897	6.3	6.1-6.4
	11 June 1903	6.2	6.0-6.4
	3 August 1903	6.3	6.1-6.5
	1 July 1911	M_I6.2	6.0-6.3
	24 April 1984	6.2	6.1-6.3
IV†	5 March 1864	5.3	5.1-5.5
	15 January 1890†	5.0	4.6-5.4
	11 December 1901†	5.0	4.7-5.3
	26 October 1943	M_L4.9	5.0-5.1
	13 June 1988	5.0	4.9-5.1
V	26 February 1864	5.6	5.4-5.8
	5 March 1864	5.3	5.1-5.5
	21 May 1864	5.6	5.3-5.9
	2 January 1891	M_I5.7	5.5-5.9
	5 September 1955	M_L5.5	5.4-5.6
	31 October 2007	5.4	5.3-5.5
VI	26 November 1858	6.1	5.9-6.3
	26 February 1864	5.6	5.4-5.8
	5 March 1864	5.3	5.1-5.5
	21 May 1864	5.5	5.2-5.8
	17 February 1870	5.9	6.1-6.3
	2 January 1891	5.6	5.4-5.8
	11 June 1903	6.0	5.8-6.2
	3 August 1903	6.1	5.9-6.3

‡ Except for the 1897 event scenario on Zone II, we consider only those pre-1911 events for which the zone location lies within Bakun's (2008) 1σ uncertainty region and for which the **M** of the recent events on the zone are within Bakun's (2008) 1σ uncertainty in **M**.

† Townley and Allen (1939) list many **M**<5.5 earthquakes near Mount Hamilton and San Jose. These data are sufficient to estimate **M** if a location is assumed.

Table 2. BPT Recurrence Interval distribution Parameters*

Recurrence	Zone I (yr)	Zone II (yr)	Zone III (yr)	Zone IV (yr)	Zone V (yr)
Mean	72	73	62	70	57
67% confidence	46-102	49-99	41-85	48-91	38-76
95% confidence	29-115	35-113	28-105	38-109	28-97
COV	**Zone I**	**Zone II**	**Zone III**	**Zone IV**	**Zone V**
Mean	0.9	0.8	0.8	0.9	0.9

* determined from Monte Carlo analysis of post-1911 earthquake occurrence on 5 Calaveras fault zone segments. Confidence bounds were calculated by counting through the distributions to determine ranges containing 67% and 95% of values.

Table 3. Earthquake probability values for 5 Calaveras fault zones*

Probability	Zone I (%)	Zone II (%)	Zone III (%)	Zone IV (%)	Zone V (%)
2010-2020					
Mean	20	18	21	17	9
Median	17	16	19	16	6
67% confidence	12-26	5-23	12-29	10-23	1-16
95% confidence	10-36	3-29	8-36	7-28	1-25
2010-2040					
Mean	49	44	52	45	42
Median	45	42	50	44	41
67% confidence	33-63	31-56	36-65	33-56	25-58
95% confidence	29-77	26-64	28-75	26-62	16-68
Forecast dates	**Zone I (yr)**	**Zone II (yr)**	**Zone III (yr)**	**Zone IV (yr)**	**Zone V (yr)**
Mean	2021	2052	2046	2058	2064
67% confidence	1995-2051	2028-2078	2025-2069	2036-2079	2045-2083
95% confidence	1978-2064	2014-2092	2012-2089	2026-2097	2035-2104

* calculated from distribution parameters given in Table 2. Values for 10-yr and 30-yr periods beginning in 2010 are given. Most likely dates for earthquake occurrence are also given based on the last earthquake times in each zone and recurrence values given in Table 2. Confidence bounds were calculated by counting through the distributions to determine ranges containing 67% and 95% of values.

Table 4. Possible historic and catalog earthquake assignment to Calaveras fault zones*

Zone I		Zone II		Zone III		Zone IV		Zone V	
26-Feb	1864	26-Feb	1864	26-Nov	1858	5-Mar	1864	26-Feb	1864
5-Mar	1864	5-Mar	1864	24-May	1865	26-Oct	1943	5-Mar	1864
26-Mar	1866	21-May	1864	20-Jun	1897	13-Jun	1988	21-May	1864
17-Sep	1888	24-May	1865	11-Jun	1903			2-Jan	1891
9-Mar	1949	26-Mar	1866	3-Aug	1903			5-Sep	1955
		2-Jan	1891	1-Jul	1911			31-Oct	2007
		6-Jul	1899	24-Apr	1984				
		20-Jun	1897						
		6-Aug	1979						

* based on magnitude and location determinations of Bakun (2008). Many earthquakes could have happened on multiple zones, which allow 134 unique combinations that are consistent with the 95% confidence interval on recurrence from Monte Carlo analysis of the 1911-present catalog. The two 1903 shocks on Zone III are inconsistent with the forecast model we applied, which either invalidates the model for Zone III, or indicates that these events occurred on a different fault.

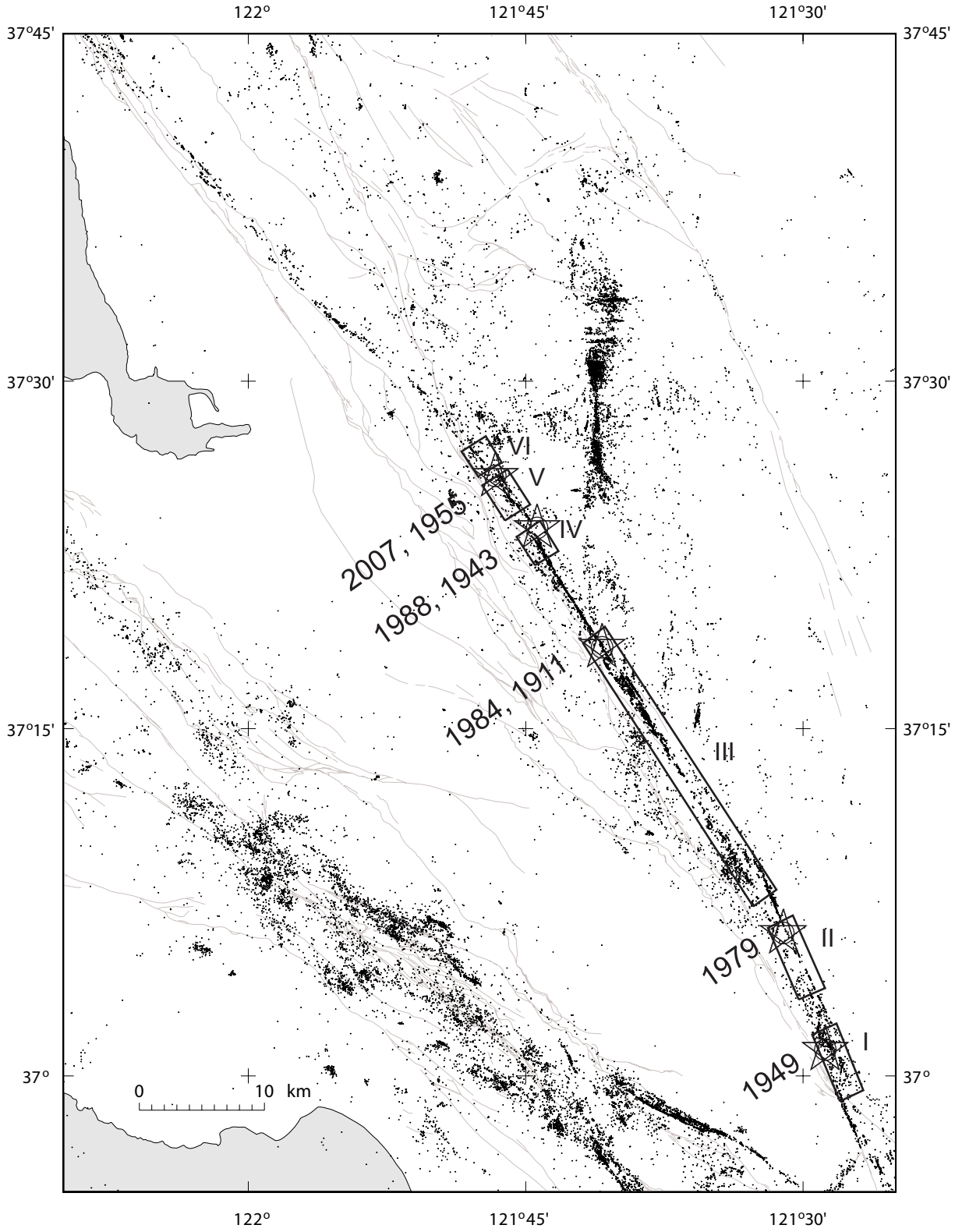
122°
121°45'
121°30'
37°45'
37°30'
37°15'
37°
VI
V
IV
III
II
I
2007, 1955
1988, 1943
1984, 1911
1979
1949
0
10 km

Figure 1

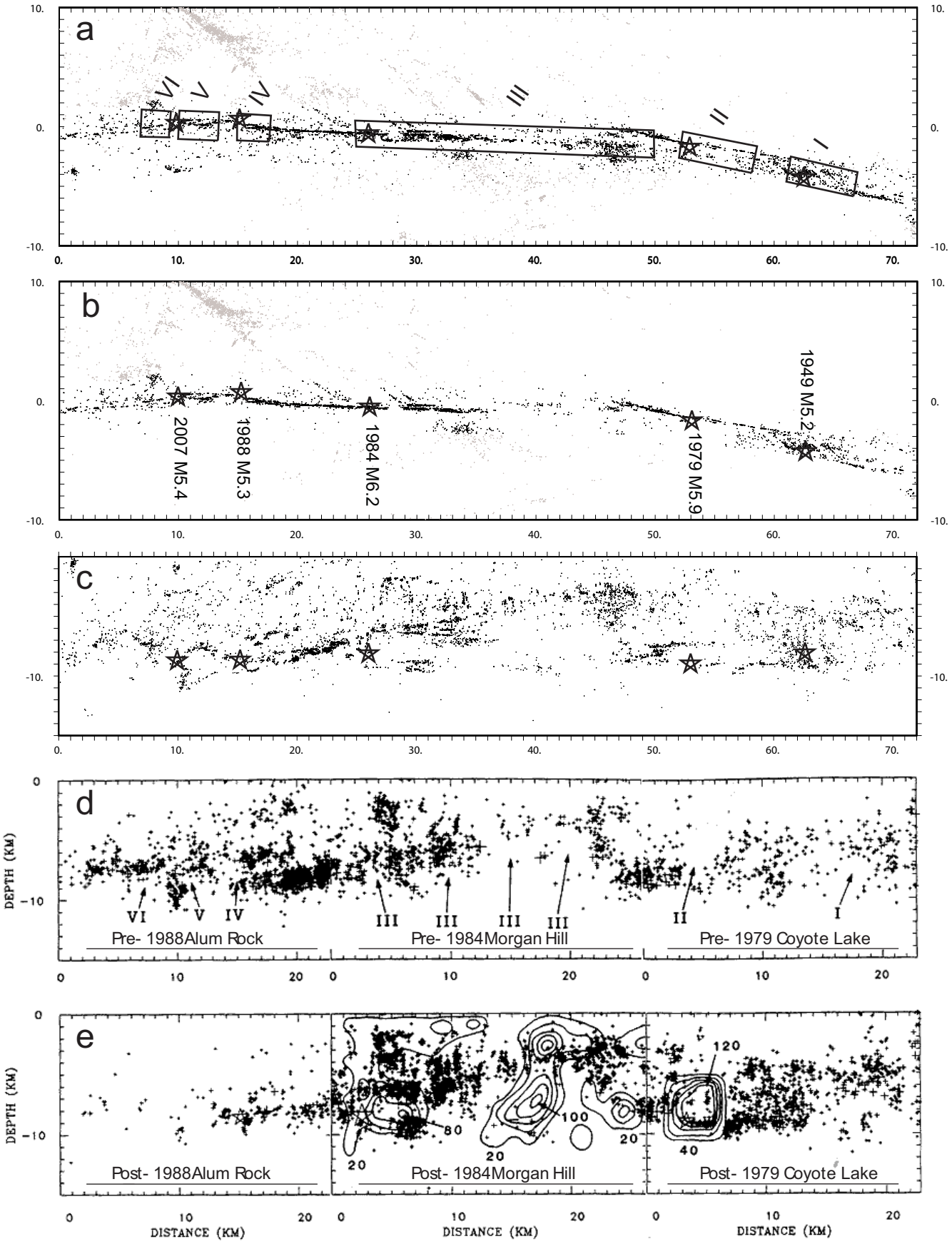
a
b
c
d
e
2007 M5.4
1988 M5.3
1984 M6.2
1979 M5.9
1949 M5.2
VI
V
IV
III
III
III
III
II
I
Pre- 1988Alum Rock
Pre- 1984Morgan Hill
Pre- 1979 Coyote Lake
Post- 1988Alum Rock
Post- 1984Morgan Hill
Post- 1979 Coyote Lake
DEPTH (KM)
DISTANCE (KM)
120
100
80
40
20

Figure 2

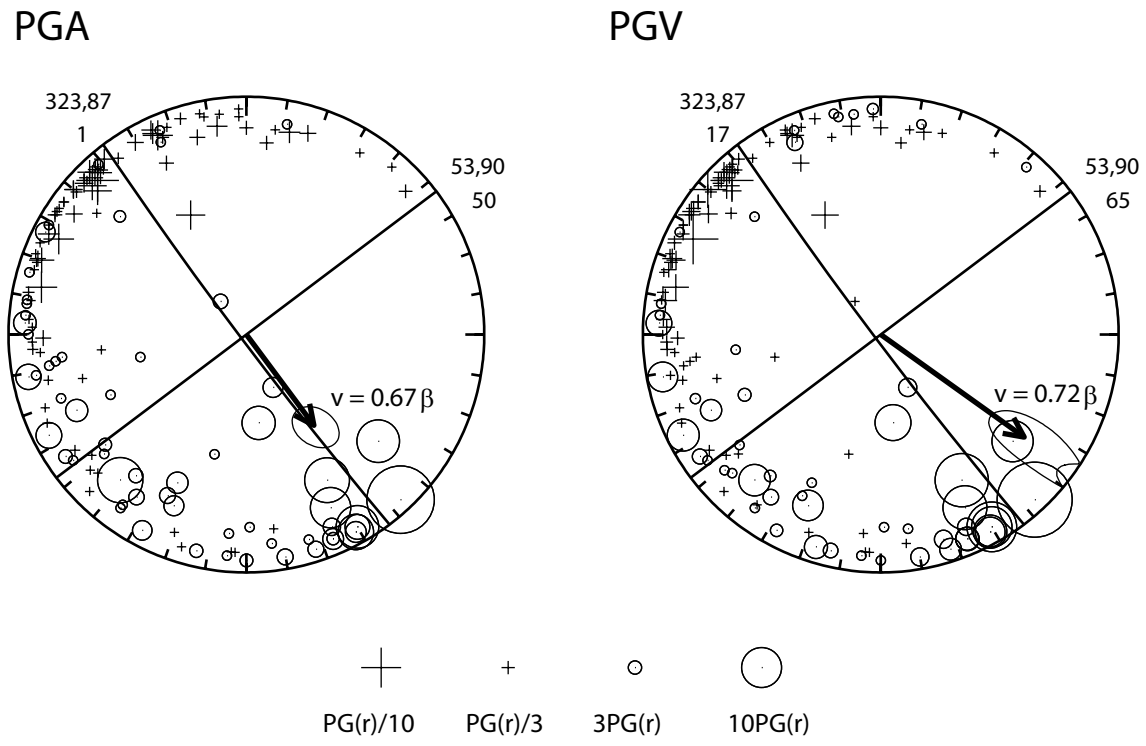
PGA
323,87
1
53,90
50
v = 0.67β
PGV
323,87
17
53,90
65
v = 0.72β
PG(r)/10
PG(r)/3
3PG(r)
10PG(r)

Figure 3

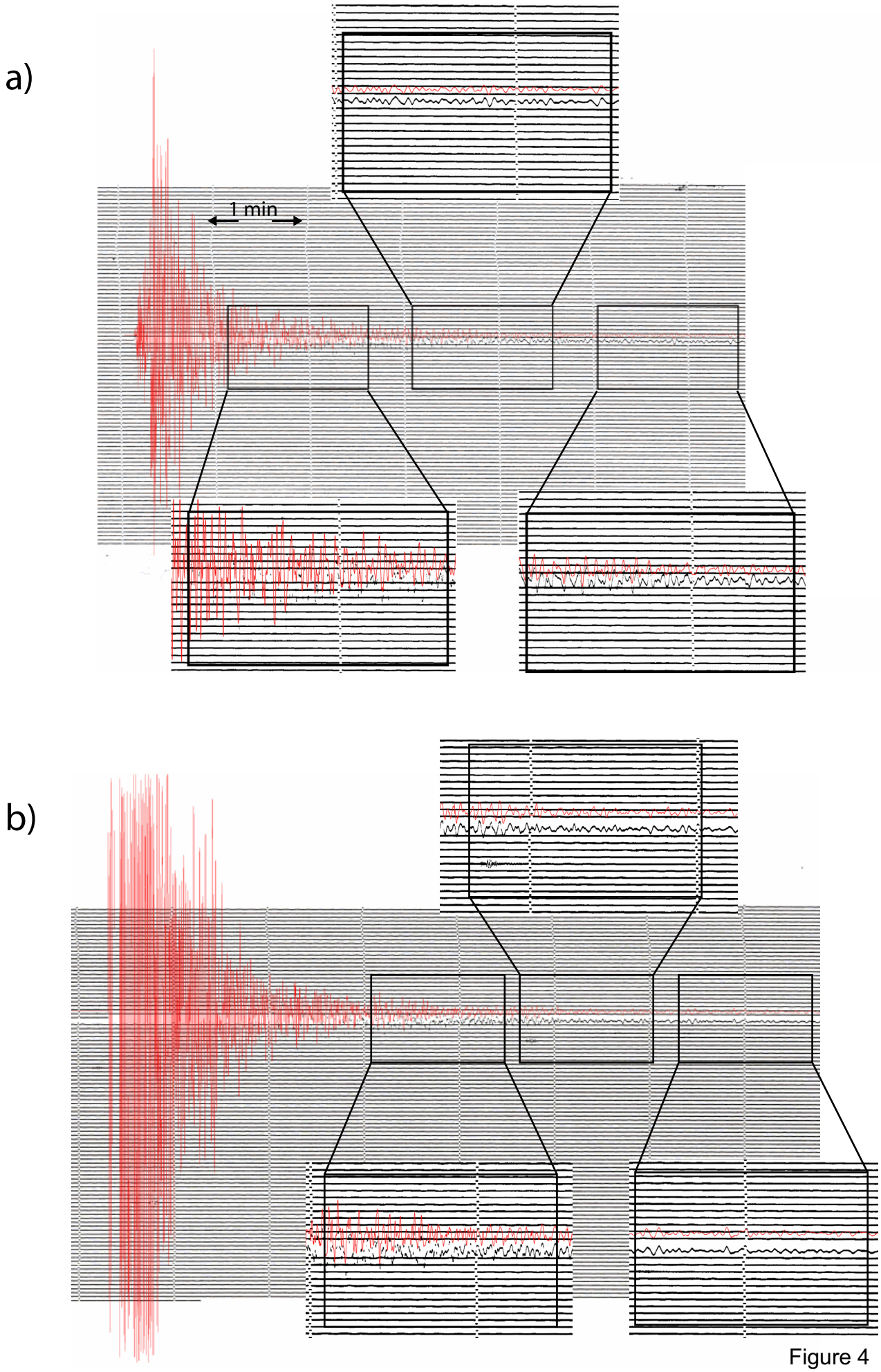

Figure 4

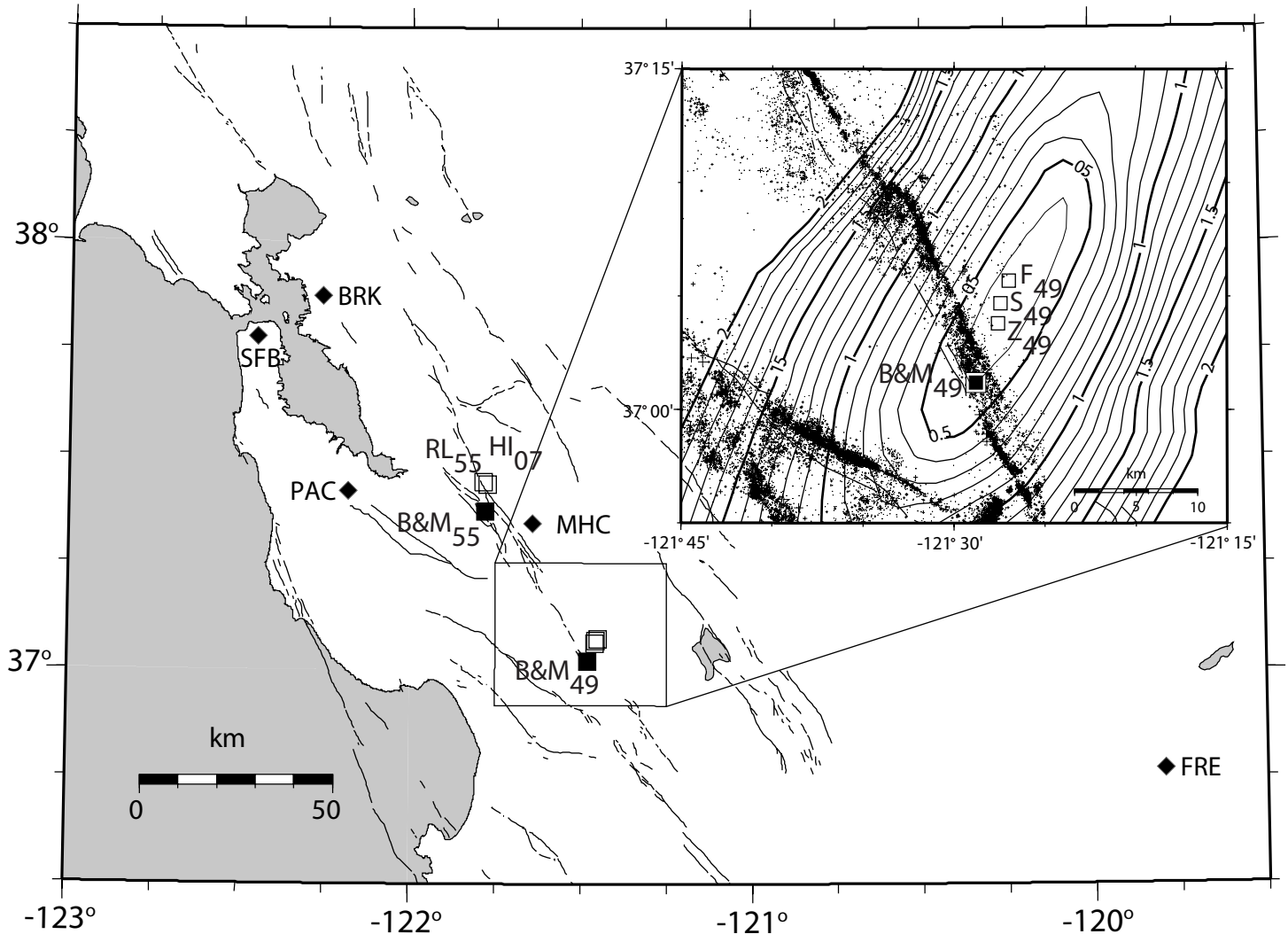
38°
37°
-123°
-122°
-121°
-120°
BRK
SFB
PAC
RL 55
HI 07
B&M 55
MHC
B&M 49
FRE
km
0
50
37° 15'
37° 00'
-121° 45'
-121° 30'
-121° 15'
F 49
S 49
Z 49
B&M 49
0.5
1
1.5
2
km
0
5
10

Figure 5

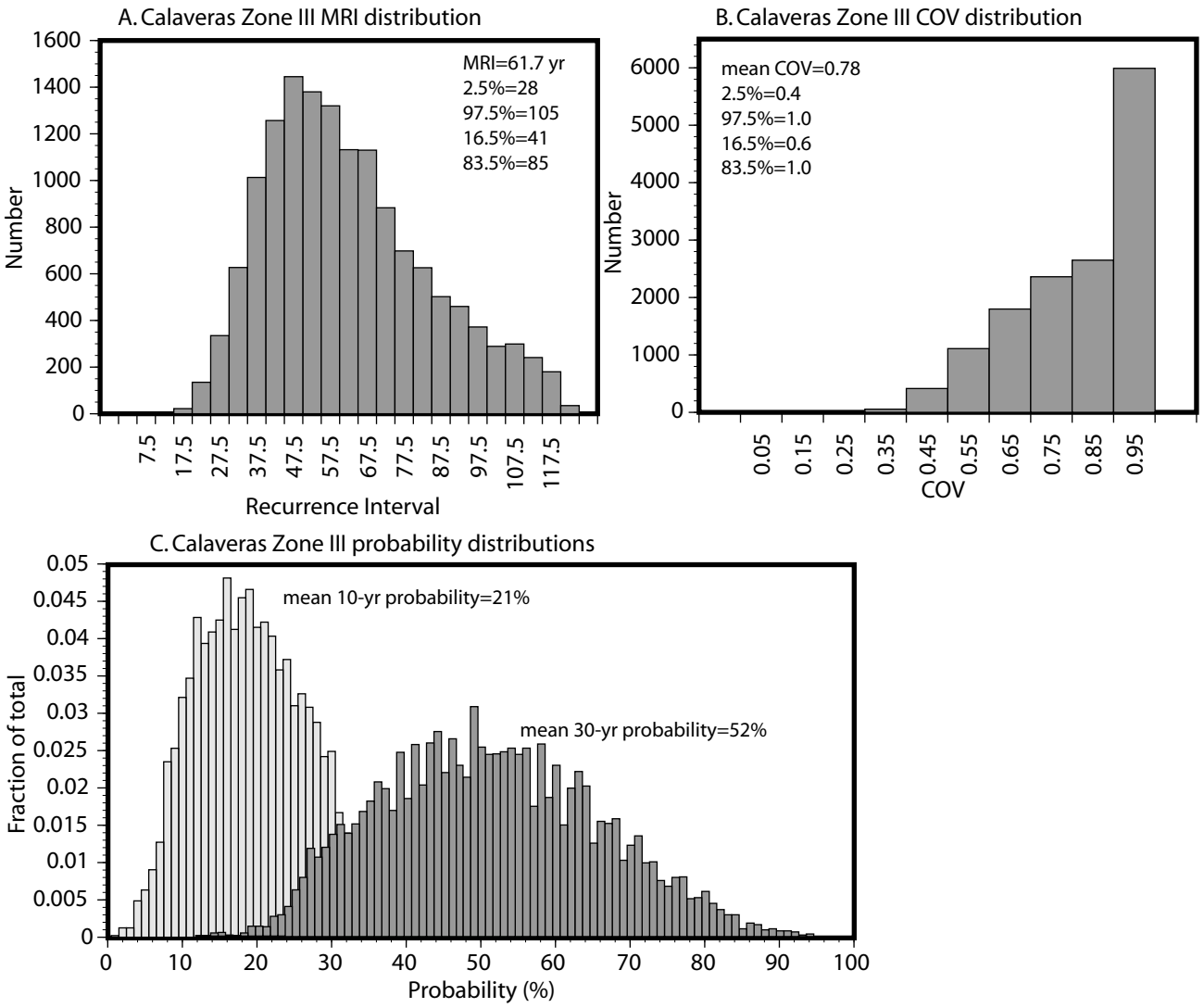
A. Calaveras Zone III MRI distribution
MRI=61.7 yr
2.5%=28
97.5%=105
16.5%=41
83.5%=85
Number
Recurrence Interval
B. Calaveras Zone III COV distribution
mean COV=0.78
2.5%=0.4
97.5%=1.0
16.5%=0.6
83.5%=1.0
Number
COV
C. Calaveras Zone III probability distributions
mean 10-yr probability=21%
mean 30-yr probability=52%
Fraction of total
Probability (%)

Figure 6

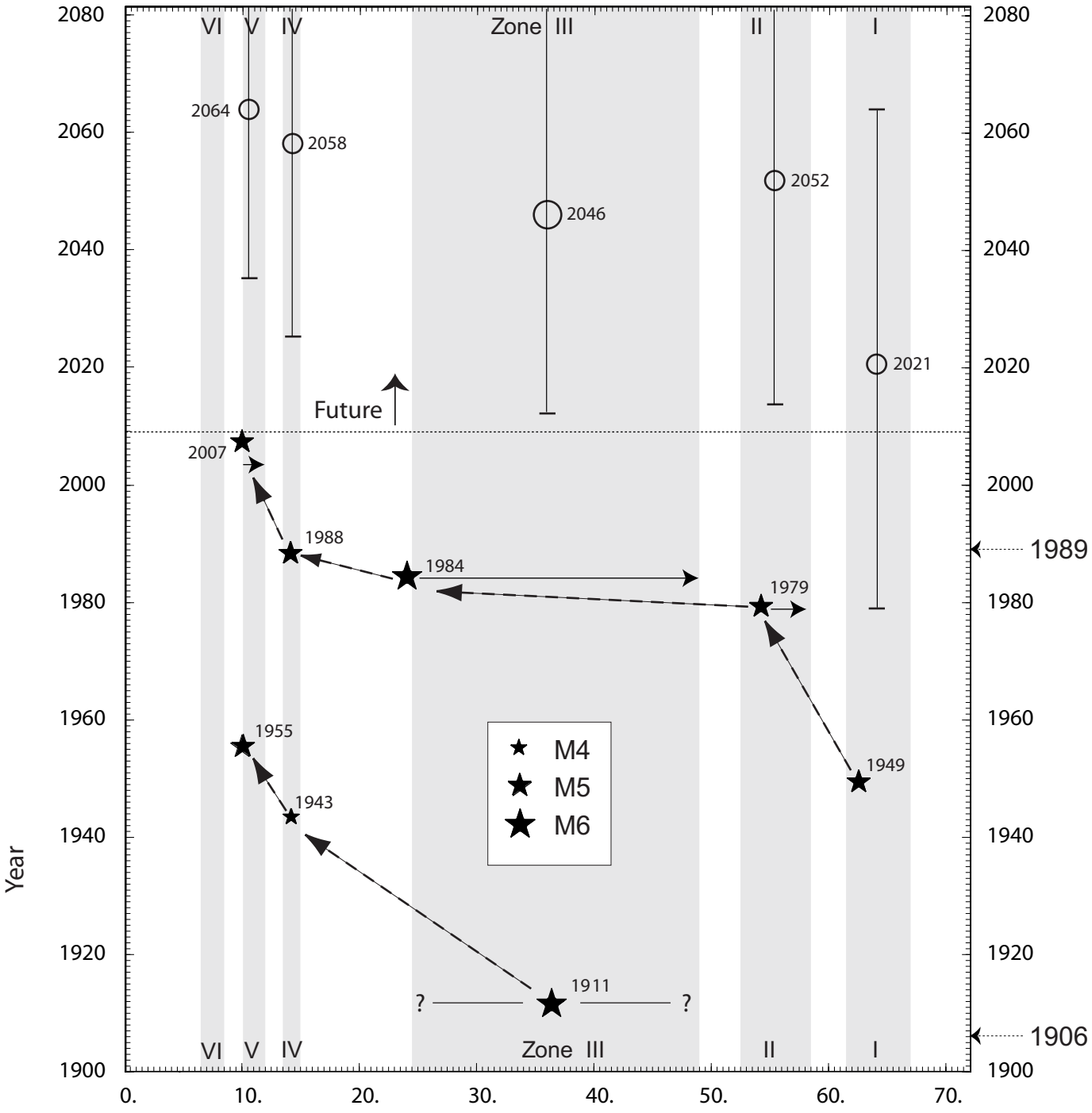
VI
V
IV
Zone III
II
I
2064
2058
2046
2052
2021
Future
2007
1988
1984
1979
1955
1943
1949
1911
?
?
M4
M5
M6
Year
2080
2060
2040
2020
2000
1980
1960
1940
1920
1900
1989
1906
0.
10.
20.
30.
40.
50.
60.
70.

Figure 7